An Overview of Utility and Mechanisms of Photonics for Power Electronics

Invited Lecture

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Acknowledgements:
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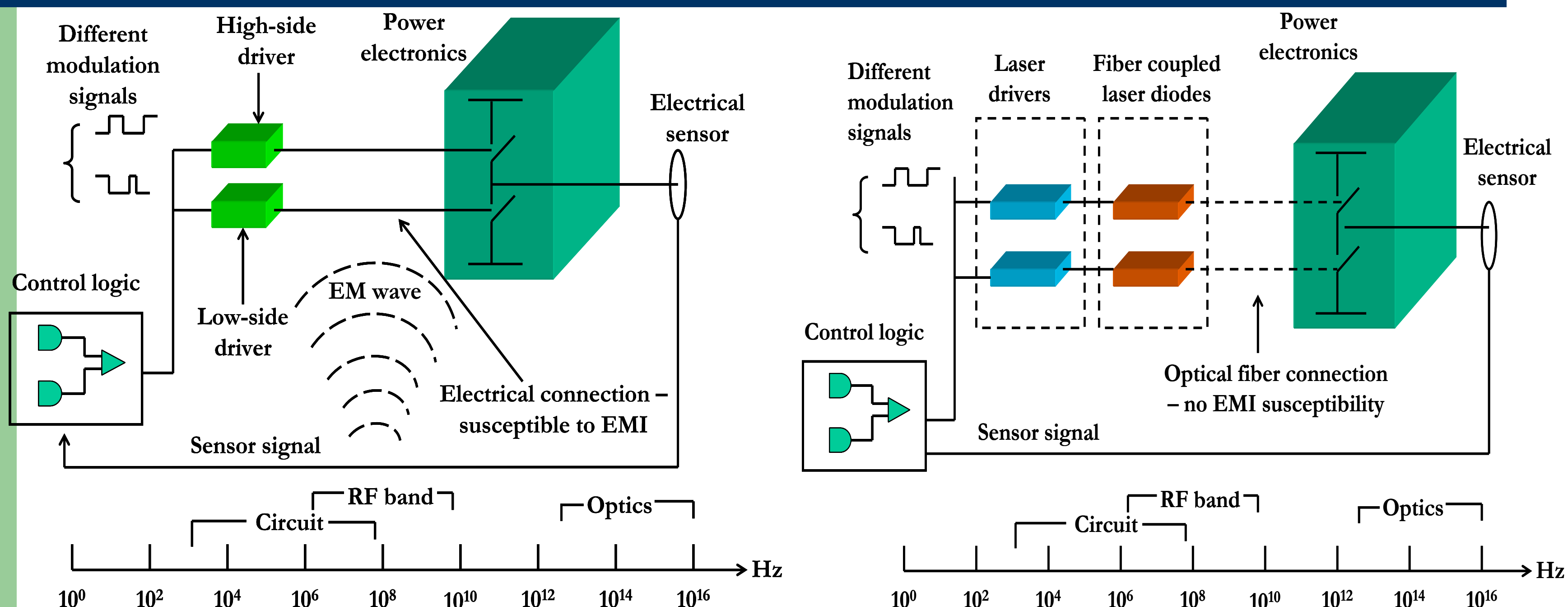
Disclaimer

The content of this presentation is covered by the following intellectual properties:

1. S.K. Mazumder, “Photonically activated single bias fast switching integrated thyristor”, U.S. Patent Application# 13281207, filed in 2011.
2. S.K. Mazumder and T. Sarkar, “Optically-triggered multi-stage power system and devices”, U.S. Patent Number 8183512, awarded on May 22, 2012.
3. S.K. Mazumder and T. Sarkar, “Optically-triggered power system and devices”, USPTO Patent# 8,294,078, awarded on October 23, 2012.
4. X. Wang, S.K. Mazumder, and W. Shi, “Insulated-gate photoconductive semiconductor switch”, USPTO Patent# 9543462 B2, awarded on January 10, 2017.

Utility of Photonics for Power Electronics (PE) [1], [2]



- Immunity from internal/external electromagnetic interference (EMI)
- Electrical isolation between power and control stages (no backpropagation)
- No need for complex floating electrical gate drivers
- Reduced device triggering delay
- Addressing issues with n&p type suitable doping for WBG/UWBG power sem. devices
- Removes requirement for high quality gate dielectrics for power sem. devices
- Dynamic modulation of device switching transition dynamics feasible with minimal excitation effort and selective excitation

Some Utility (Application) of Photonic PE: *Power Grid (HV/MV)*

Static Var Compensator (SVC)

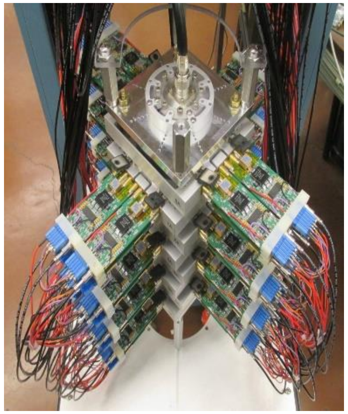
High Voltage Direct Current (HVDC)

StatCom

Solid-State Transformer

Solid-State Fault Current Limiter

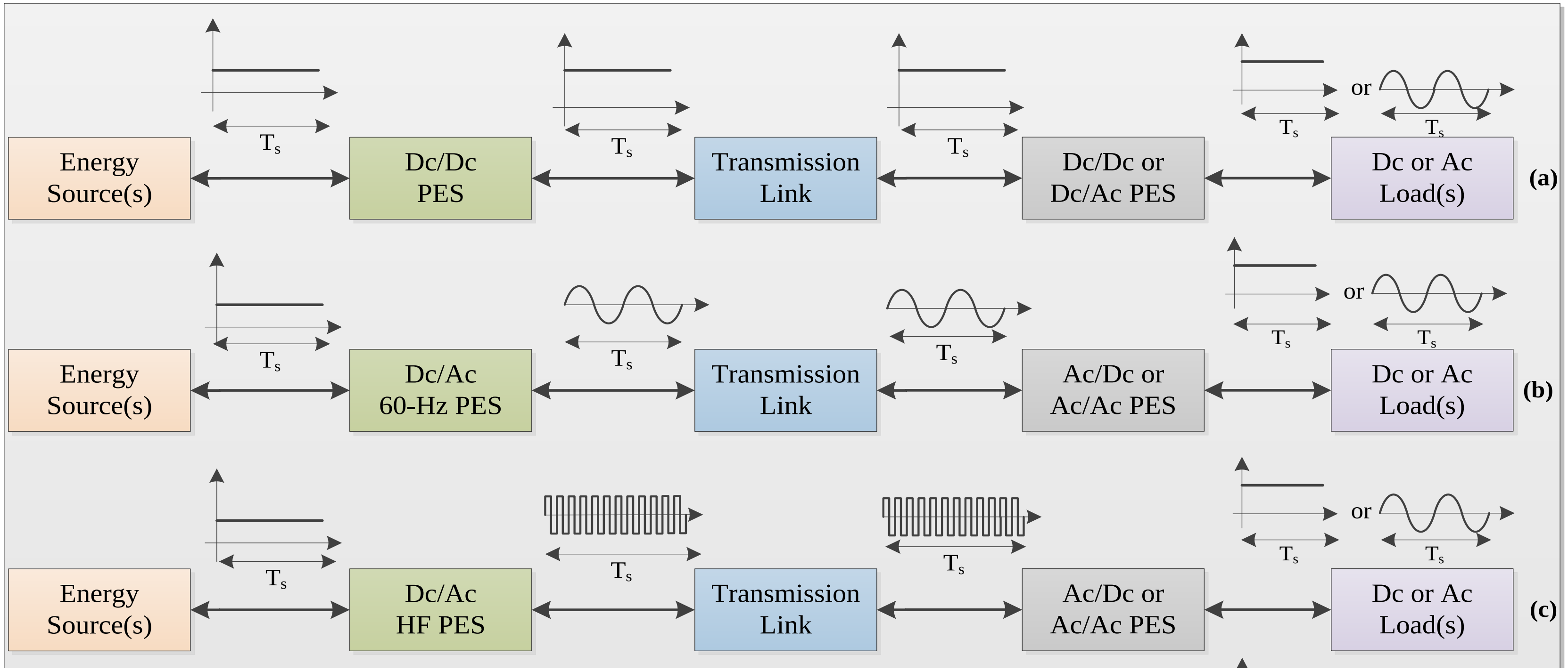
Pulsed Power System



Source: Multiple Google Sites

Some Utility (Application) of Photonic PE:
Discretized HF Power Transfer (LV/MV) (Patented) [3]-[5]

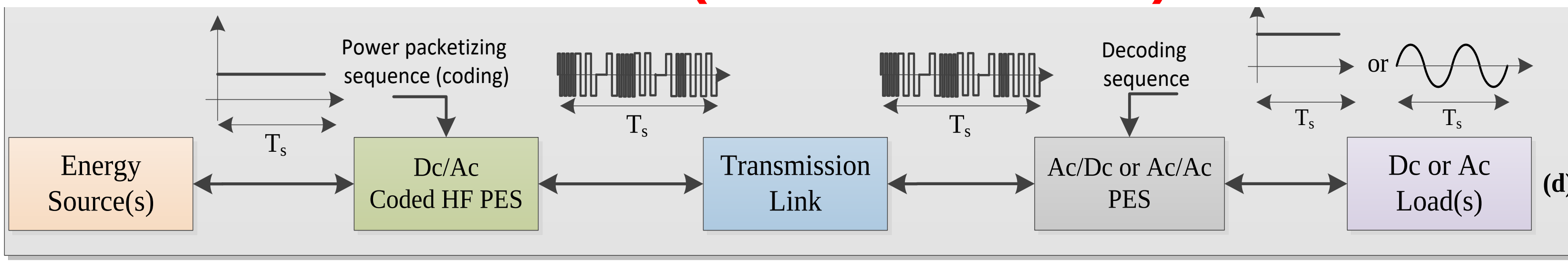
Traditional Power Transfer

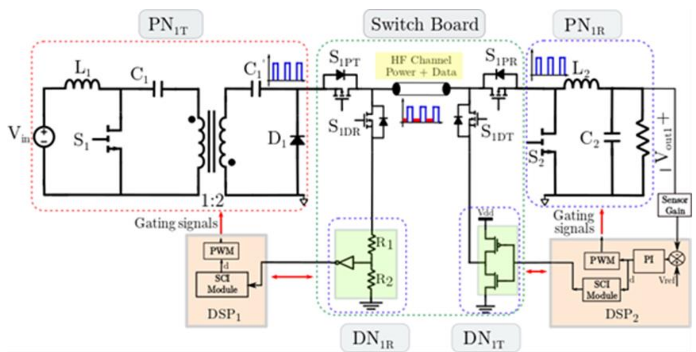


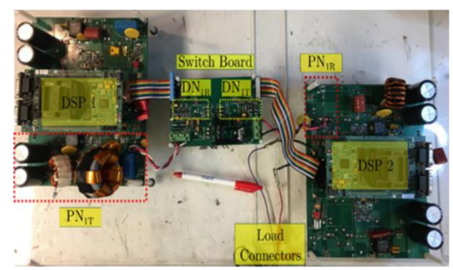
Some Utility (Application) of Photonic PE:

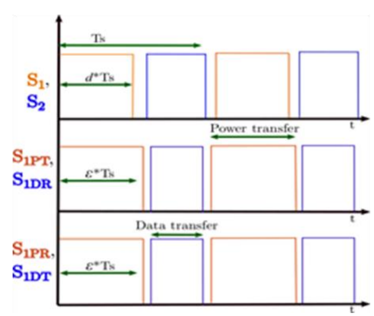
Discretized HF Power Transfer (LV/MV) (Patented) [3]-[5]

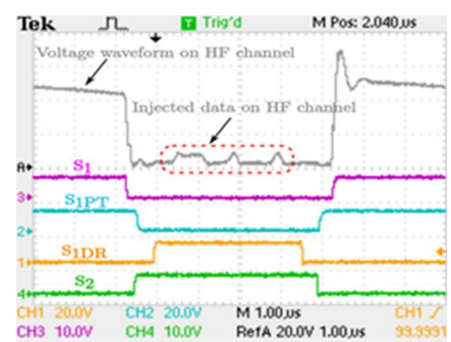
Coded Asynchronous Multi-Scale High Frequency Power Transfer (Patent Protected)











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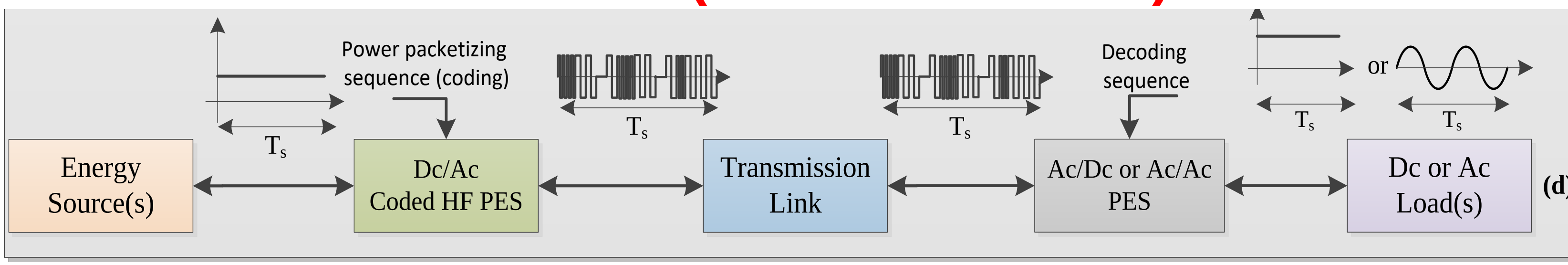
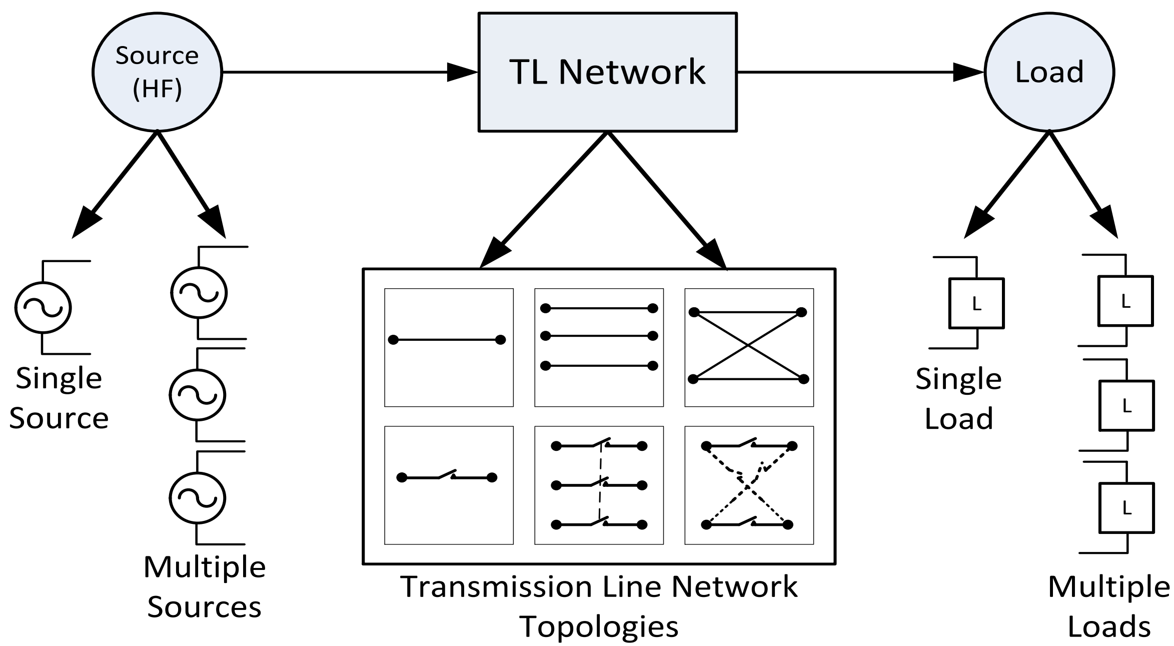


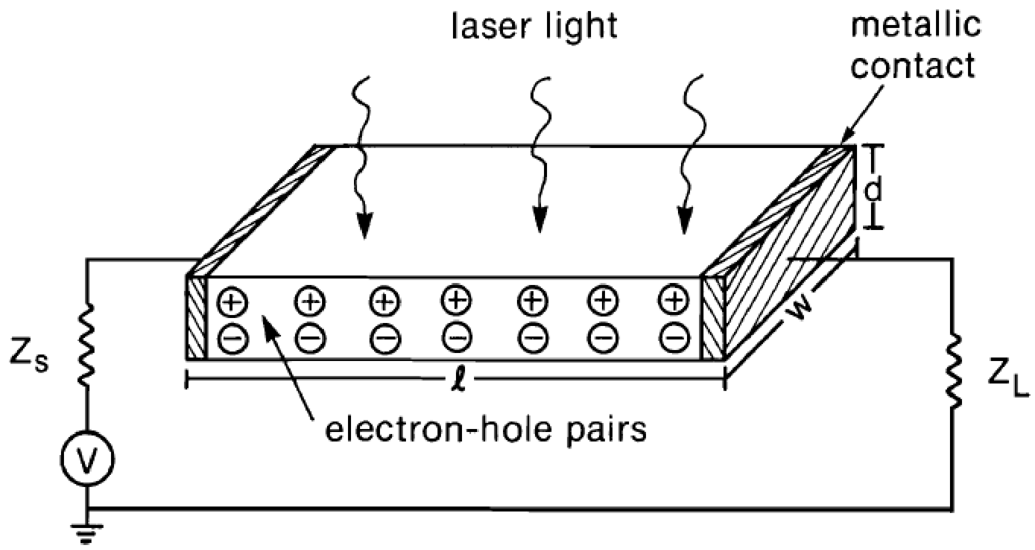


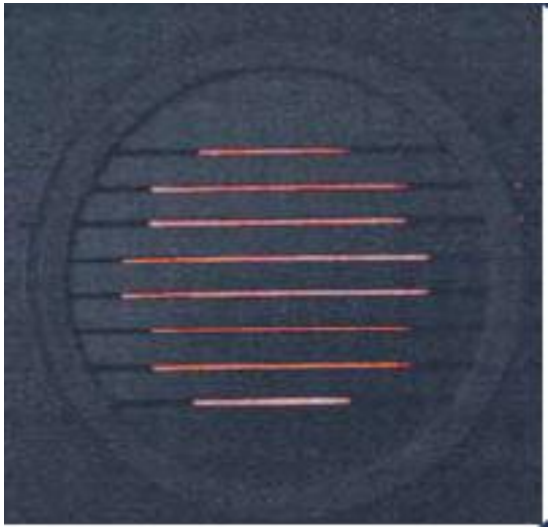
Requirements of PE from (Optical) Power Semiconductor Devices (PSDs)

- ❑ Low cost
- ❑ Low leakage
- ❑ Low on-state drop
- ❑ Low optical power
- ❑ Moderate to high repetition rate
- ❑ Wide variation in duty cycle
- ❑ Fast switching dynamics
- ❑ Reduced dv/dt and di/dt stress
- ❑ High reliability (electrical, mechanical, thermal stabilities)
- ❑ Low device complexity
- ❑ Low drive complexity

Mechanisms of Optical PSD: *Low Rise Time [6]*

PCSS





- High speed device turn on
- Minimum light activation to actuation delay
- Relatively simple device structure
- No gate dielectric

- Triggering efficiency low
- Triggering cost could be high
- Duty cycle typically small
- Current filamentation problem

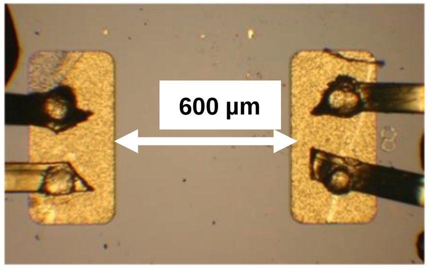
Source: Sandia, Empfasis

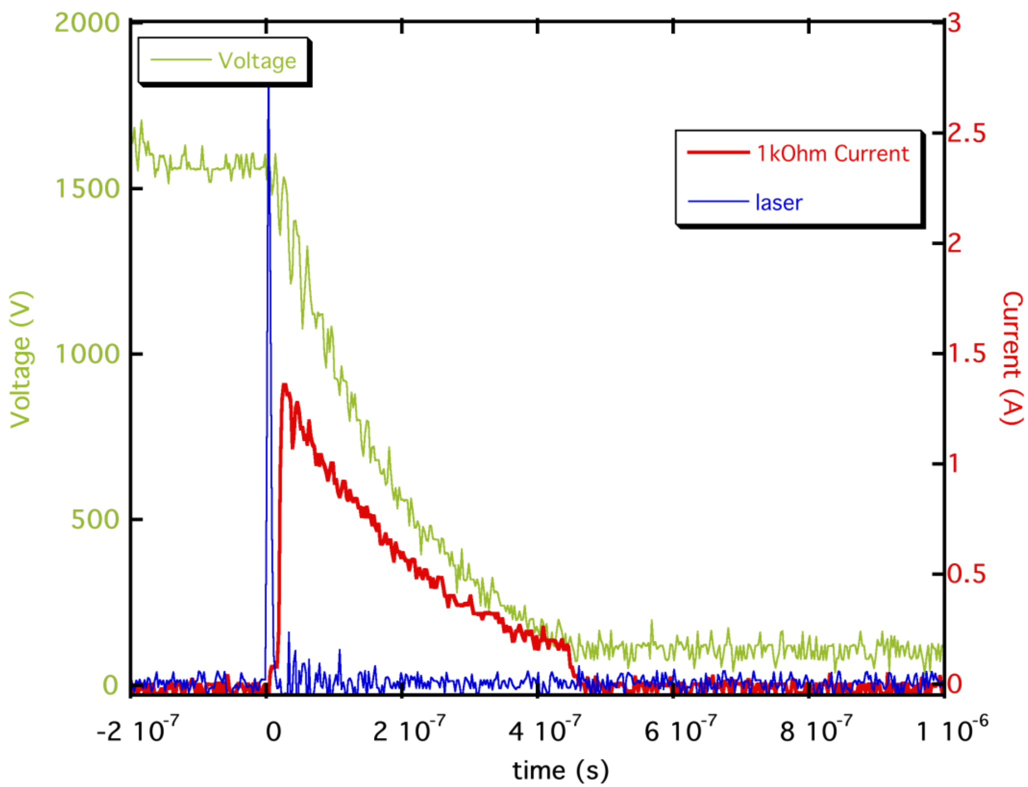
Mechanisms of Optical PSD: *Low Rise Time with Reduced Optical Power and/or Cost [7]-[9], [13], [14]*

GaN PCSS

Cross-Section Diagram of GaN PCSS

Optical Image (top view) of GaN PCSS

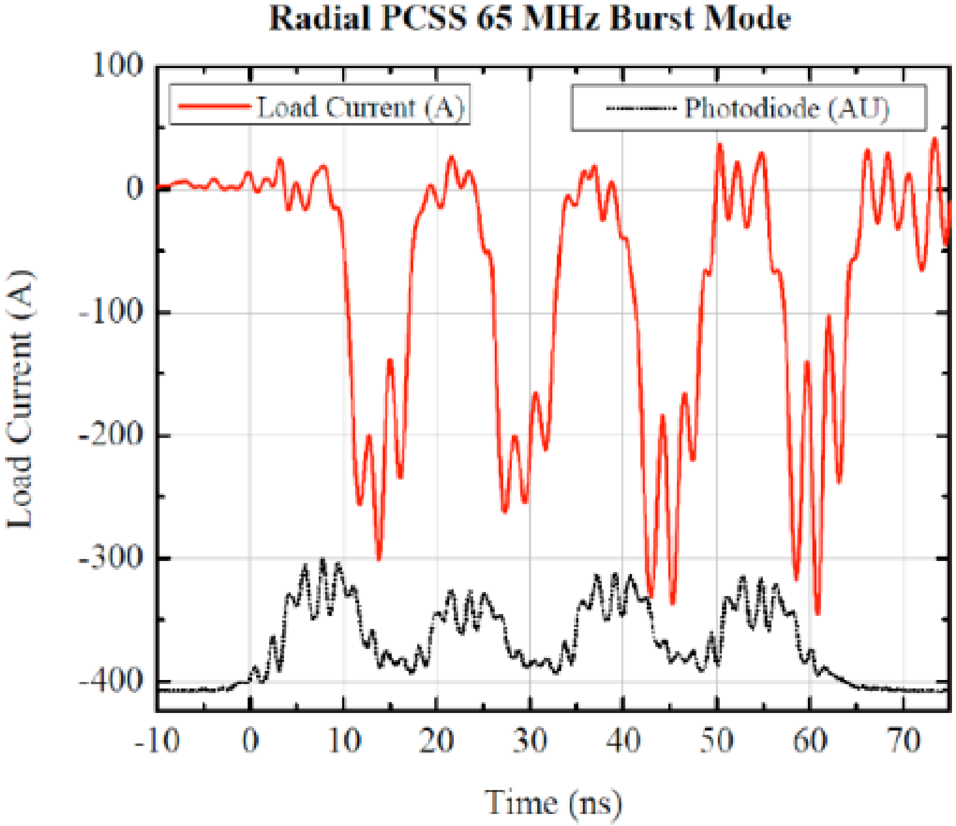




Source: Sandia, Texas Tech, UIC LLNL

Mechanisms of Optical PSD: *Low Rise Time with Reduced Optical Power and/or Cost [7]-[9], [13], [14]*

Vertical PCSS switch capable of holding-off up to 50 kV

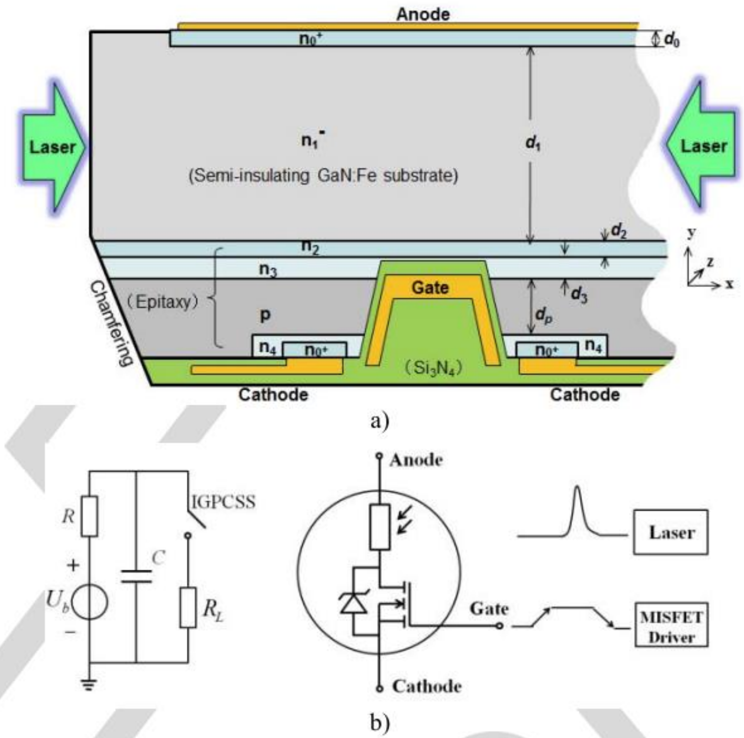


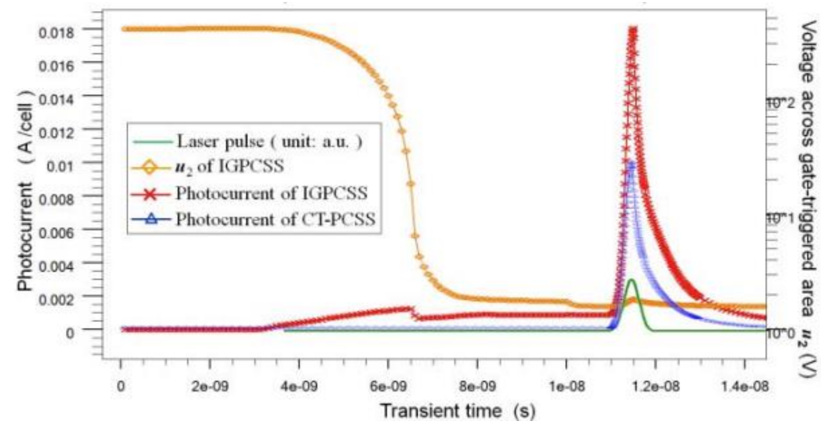
20 kV 65 MHz burst mode switching into 50 Ω

Source: Sandia, Texas Tech, UIC LLNL

Mechanisms of Optical PSD: *Low Rise Time with Reduced Optical Power and/or Cost [7]-[9], [13], [14]*

GaN Hybrid PCSS (UIC)

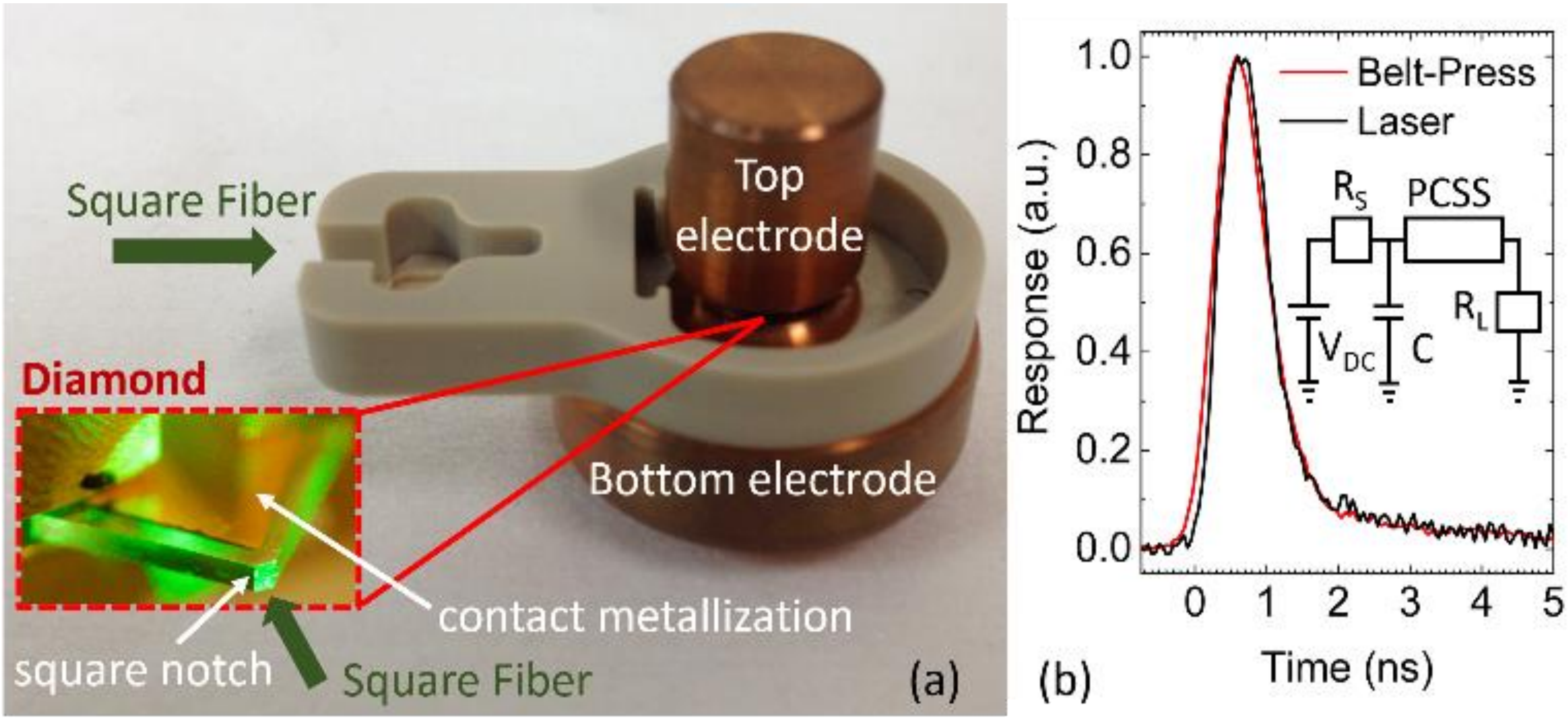




Source: Sandia, Texas Tech, UIC LLNL

Mechanisms of Optical PSD: *Low Rise Time with Reduced Optical Power and/or Cost [7]-[9], [13], [14]*

UWBG (Diamond) PCSS



- Higher speed device turn on
- Mid-bandgap laser reduces cost

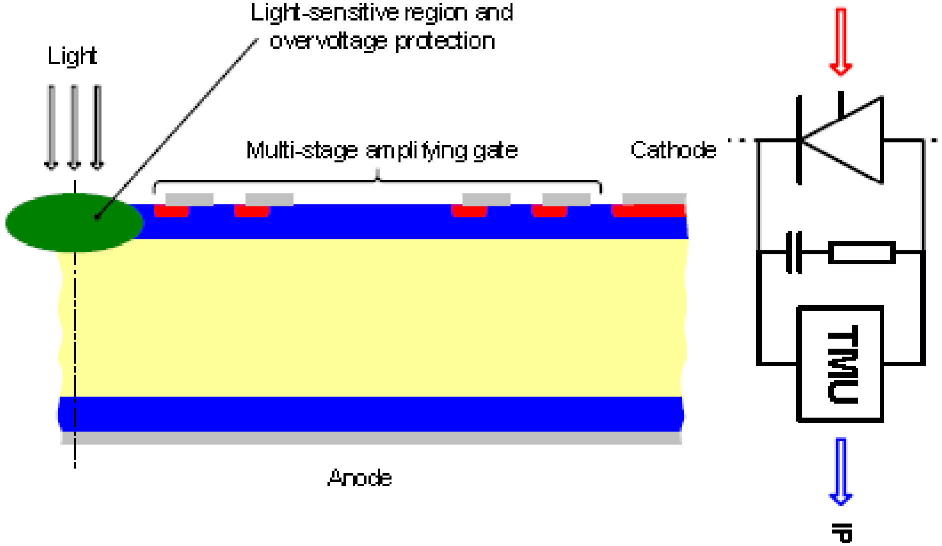
- Enhanced device cost
- Reduced laser utilization

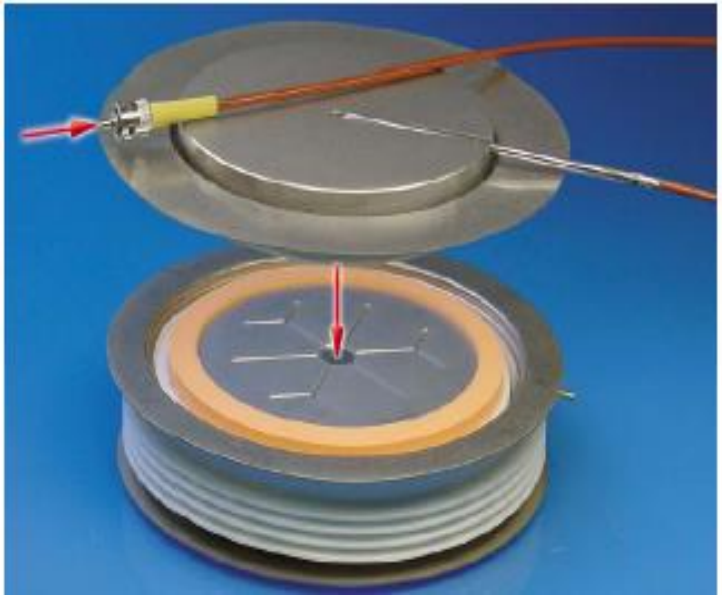
Source: Sandia, Texas Tech, UIC LLNL

Mechanisms of Optical PSD:
Low Optical Power [6]

FP: Firing pulse
IP: Indicating pulse

LTT





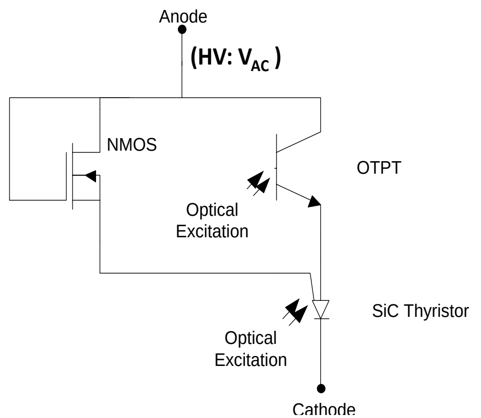
- Smooth turn on
- High device gain
- Very low optical triggering power due to pilot thyristor
- Device real-time status available

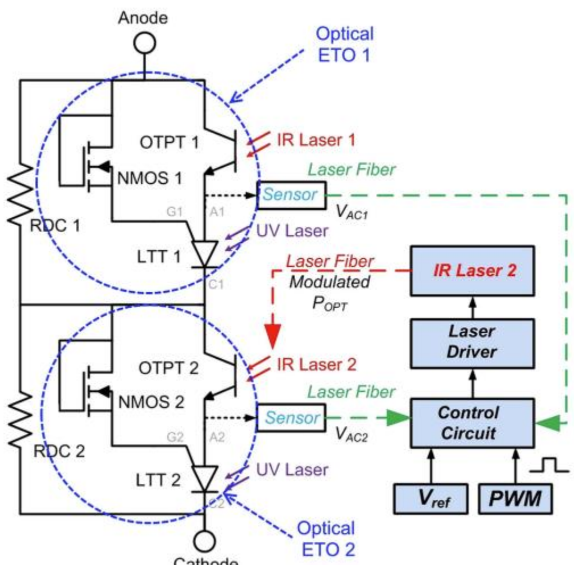
- Turn off is slow
- Gate drive is complex and lossy since it has to handle large turn-off current
- Integrated device structure complex

Source: Siemens

Mechanisms of Optical PSD:
Low Optical Power and Faster Switching [6],[10],[11]

SiC Optical ETO (UIC)



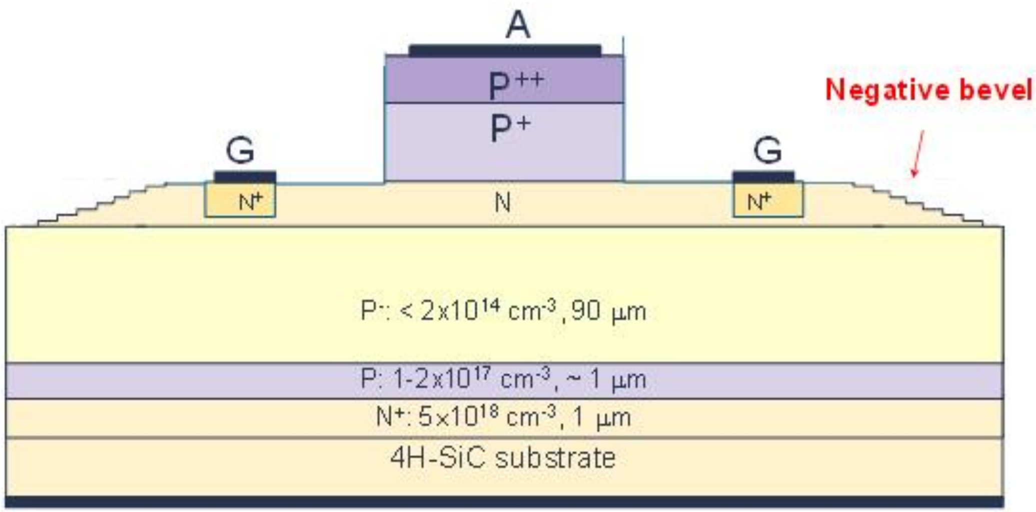


Series Connection

- No control bias required
- MF operation feasible
- Different materials can be used
- Dynamic modulation possible
- Series connection possible

- …..

Mechanisms of Optical PSD:
Low Optical Power and Faster Switching [6],[10],[11]



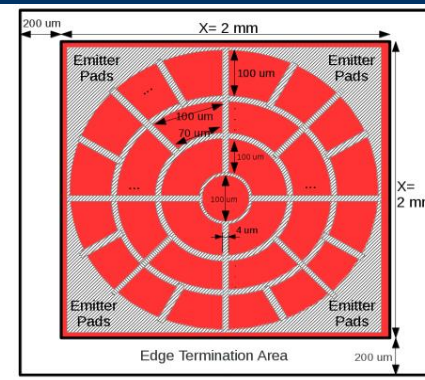
SiC 12-kV Thyristor Structure with Beveling C

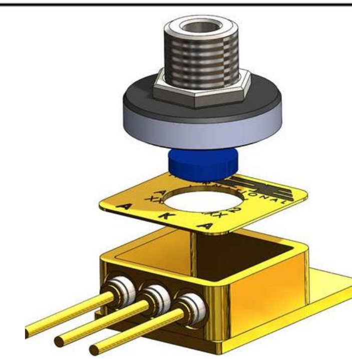
SiC VHV Thyristor Die

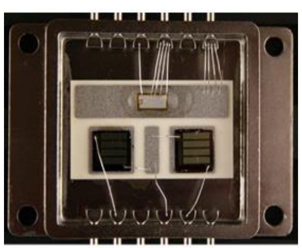
SiC VHV Thyristor Module

Acknowledgement: ARL, SPC

Acknowledgement: Cree, Silicon Power



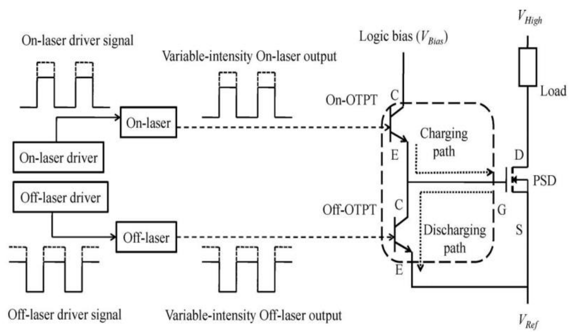


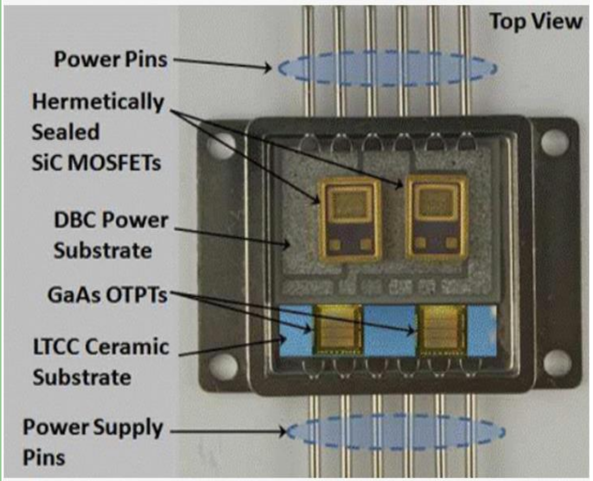


OTPT

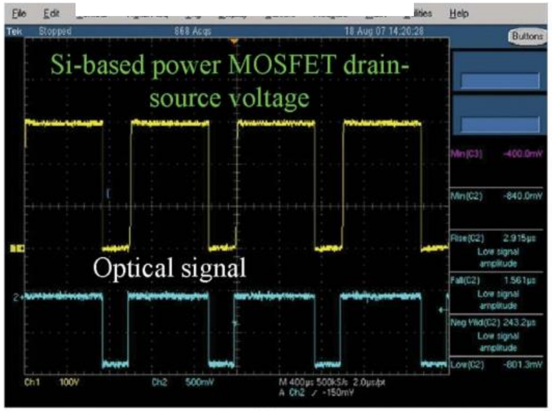
Acknowledgement: UIC

Mechanisms of Optical PSD:
Optical Gate Driven Insulated Gate PSD [12]



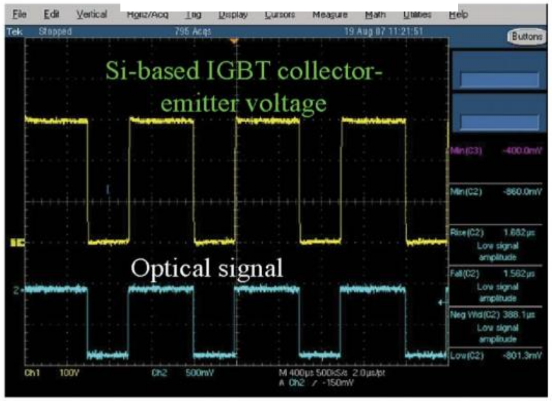


Si MOSFET

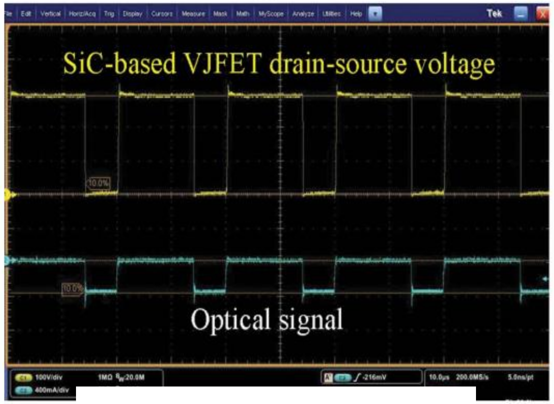


(a)

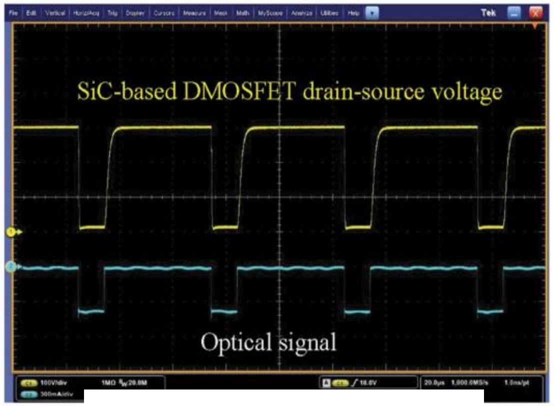
Si IGBT



(b)



SiC VJFET



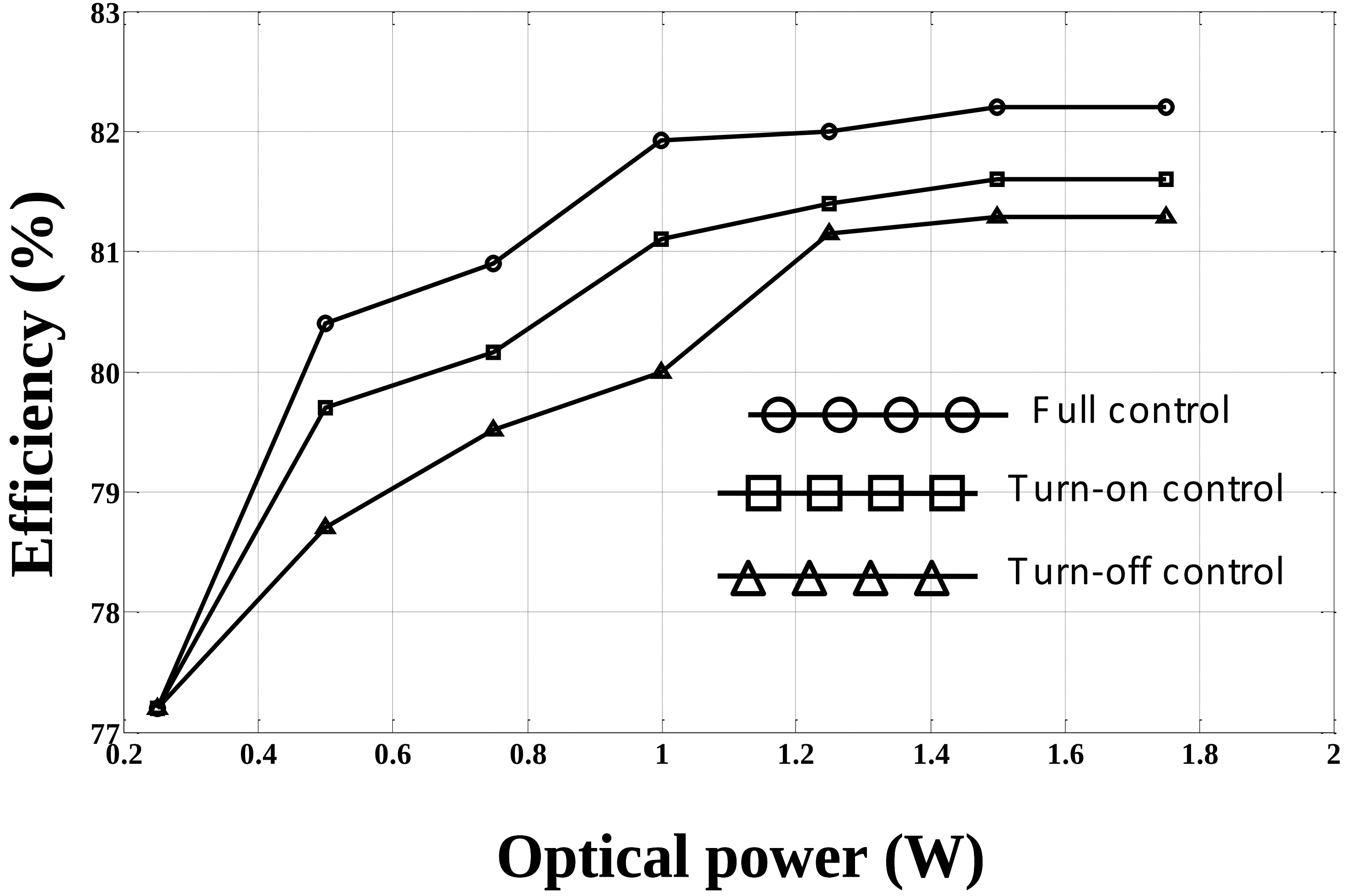
SiC MOSFET

- Triggering wavelength is unchanged
- Separation of power and control

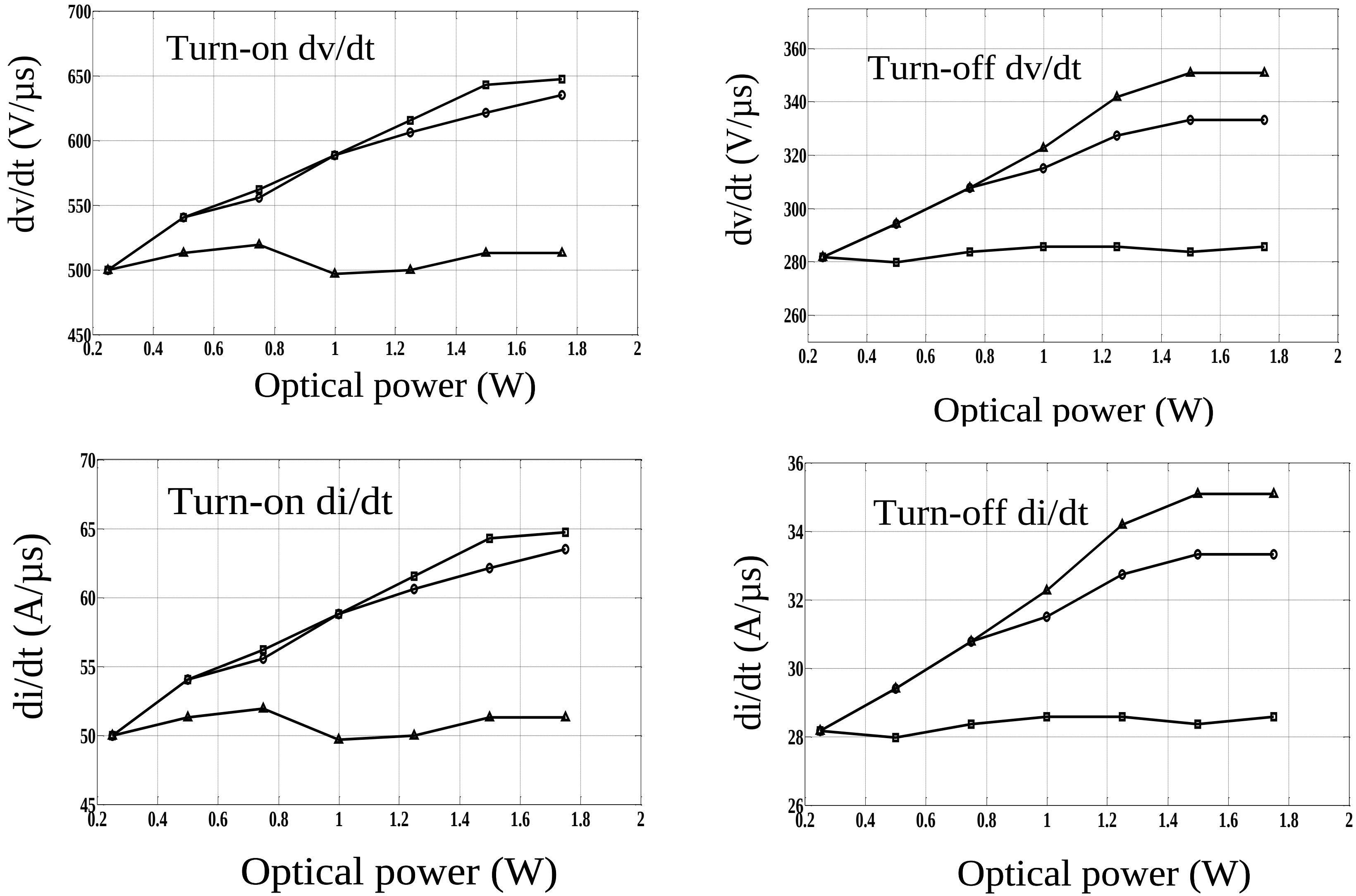
- Higher onset delay
- No direct photogeneration

Source: UIC

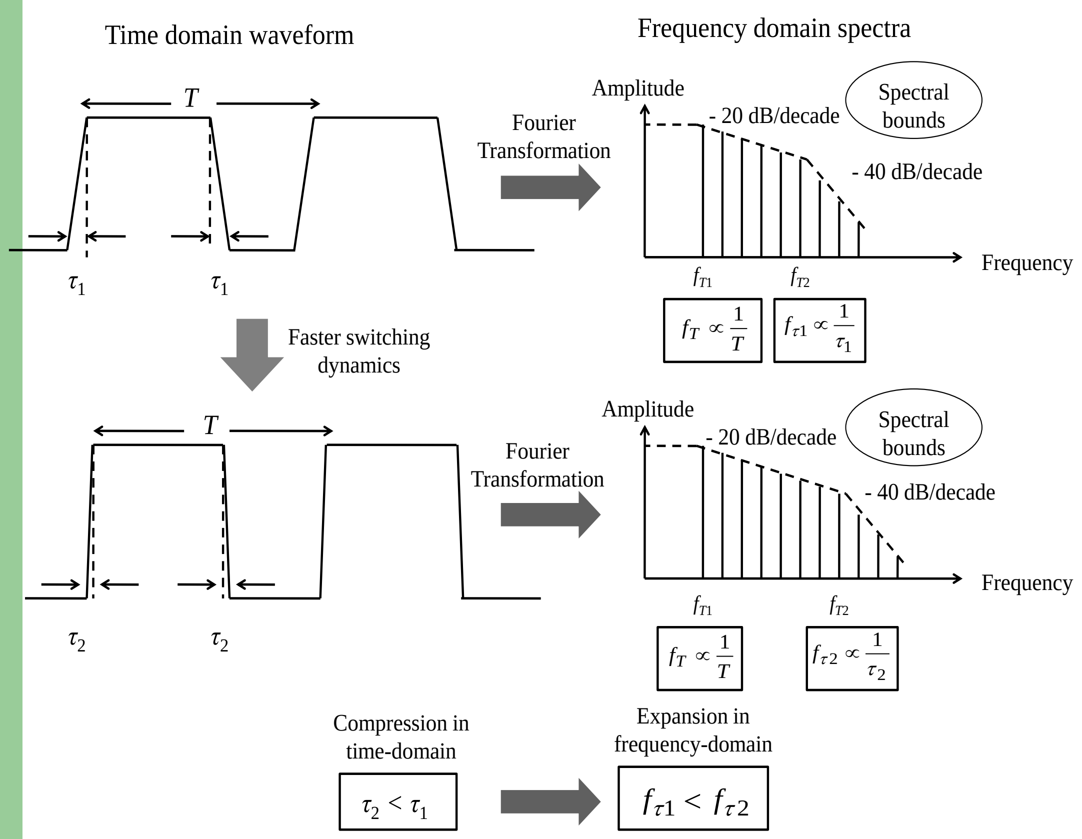
Mechanism for Optical Control: *Experimental Illustrations [12]*

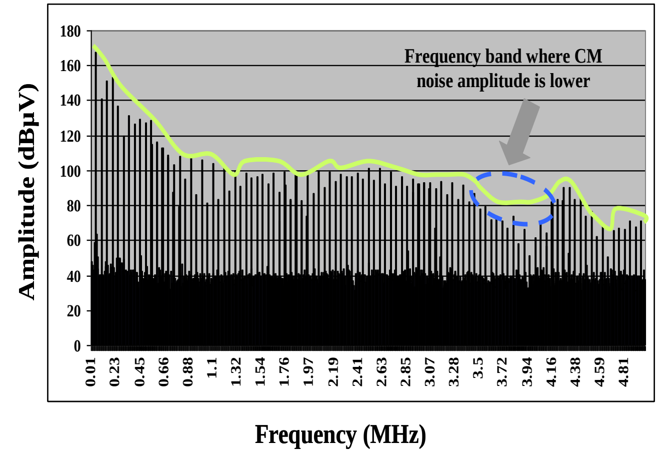


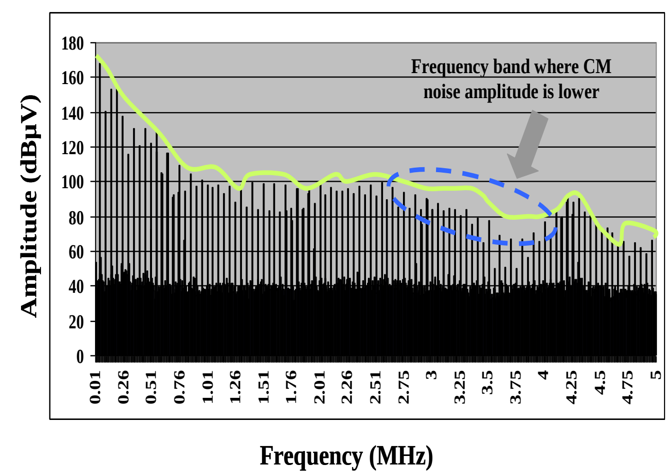
Mechanism for Optical Control: *Experimental Illustrations [12]*



Mechanism for Optical Control: *Experimental Illustrations [12]*







Summary

1. Optically-controlled PSDs yield several device and system level advantages which can have direct impact on the reliability, efficiency, simplicity, controllability, and form factor of the PE based next-generation energy system / grid.
2. Innovative photonic MV/HV PSDs that leverage several superior properties of UWBG/WBG materials to yield key performance metrics (e.g., high gain, low leakage, low loss, low rise/fall times, wide duty cycle etc.) and support the goals of PESs outlined in “1” are a necessity.
3. A key aspect of that device-system connectivity, depends on how these optical UWBG/WBG PSDs are innovatively controlled to mitigate their impacts on the system environment and vice-versa and achieve multi-scale optimality of the next-generation PES.

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Thank You!

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